

PALE BLUE DOT 11 –SESSION 2 TALKS – SLEEP, ZAHNLE, KASTING (TO BE ADDED), TRAUB (TO BE ADDED), DE PATER

Norm Sleep talk

As a planet evolves thermally by cooling, the tectonic style of its crust can pass through the following phases: global magma ocean, plate tectonics with multiple plates, and single plate tectonics. Internal heat is insignificant in maintaining temperatures at the planet's surface, except very soon after accretion. Perhaps Venus and Mars once had plate tectonics. A decline in tectonic activity by itself cannot necessarily affect the atmospheric O₂ budget, because the decline weakens both the sources (uplift, erosion and sedimentation which buries photosynthetic organic carbon) and sinks (reduced volcanic gases, and uplift of oxidizable rock materials). The balance between radiogenic heat production and heat flow to the planetary surface is rarely balanced at any instant in time. Instead, the ratio of heat generation to heat flow tends to vary above and below unity as the tectonic style of the crust switches back and forth between styles that are more efficient (e.g., multiple plate tectonics) or less efficient (e.g., single plate tectonics) in dissipating internal heat.

Basaltic rock has relatively high iron contents and so it consumes relatively more O₂ and sulfate during weathering. Aqueous weathering of basalt releases a number of chemical constituents that are useful for life. Aqueous thermal alteration of basalt, either by impacts or by geothermal heating, consumes CO₂ and O₂. Hydration, followed by remelting, produces melts that are more silica-rich.

It is useful to compare the relationship between tectonics and gravity. Gravity scales to planetary surface area. Pressure is the product of gravity, rock density and depth beneath the surface. Thus the interior pressure gradient scales to gravity and interior pressure scales to the square of the planetary radius. Pressure-temperature space was similar among terrestrial planets, early in their history. Smaller planetary bodies cool faster with time. Thus the fracture system in the crust of a smaller planet tends to extend deeper and it provides a larger sink for reactive volatile constituents.

To accumulate O₂ in the atmosphere, one must bury organic matter in sedimentary rocks, principally shales. Tectonics drives the crustal uplift, weathering and erosion that sustain shale production. Shales deposited on the relatively stable continental crust promote O₂ accumulation because they sequester organic carbon for geologically-longer periods. Also, continental crust contains relatively less iron than basalts, therefore it consumes less O₂

during weathering. About one-third of Earth's surficial water inventory is buried in the crust.

If the Earth had about half of its present water inventory, the oceans would largely disappear. If the water inventory were twice as large, the landmasses would be largely submerged.

Thus Earth's present circumstance seems optimal for producing a Pale Blue Dot, but it also seems to lie on a rather narrow optimum. However, we really do not understand the processes that control the inventories of surface water and atmospheric O₂. Tectonics has been declining for a long time, but the regulation of O₂ levels seems to involve factors that are more subtle.

Kevin Zahnle talk

The key events in Earth's early history can be depicted along a time-line. The sequence of events are the origin of the solar system at 4.56Ga, the moon forming impact at 4.45Ga or so, the rise of O₂ at 2.1Ga and also perhaps just prior to 0.54Ga, the time at which multicellular life emerged so dramatically in the fossil record. In our solar system, one can imagine that perhaps ten potentially habitable worlds once existed. These include Venus, Orpheus (the planet that hit Earth to make our moon), Mars, Europa, Ganymede, Callisto, Titan, Triton and Pluto. Ganymede and Callisto might have subsurface liquid water like Europa, but it would be deeper inside. Titan seems more promising because it has organic matter in addition to the water. Triton and Pluto seem even more promising, because they are big melted comets.

Regarding atmospheres, they can be either reducing or oxidizing depending on whether they are exporting oxidized materials faster than reduced materials, or vice versa. Three ways to add reduced equivalents to the atmosphere are adding reduced volcanic gases, subducting ferric iron or subducting water. Oxidizing power can accumulate in the atmosphere either through hydrogen escape to space or by burial of reduced carbon. The role of the mantle is important because the mantle is so big and therefore it has a large volatile inventory. About 2% of the iron in the mantle is ferric. About 0.6 oceans of water would have been required to oxidize that iron (and produce a lot of hydrogen in the process). This might have happened during the Archean (3.9 to 2.5Ga). Even earlier, large impacts deposited siderophilic (iron-loving) elements in the mantle. When "Orpheus" impacted the Earth, its iron core contributed much of this siderophile inventory. This translates to about 10²³ moles of iron, equivalent to two oceans of water. Thus an enormous pulse of reducing power was deposited about 100 Ma after Earth formed, when conditions were otherwise rather similar to today. This is the time when I believe that the origin of life could have occurred. The mantle's ferrous iron inventory would need about 50 oceans of water to be oxidized. Thus the oxidation of the mantle would produce abundant hydrogen, much of which escaped.

If life ceased, weathering would remove atmospheric O₂ in about four million years.

Regarding atmospheric CO₂ levels, the level inferred from the Rye and Holland study of 2.7 Ga rocks is insufficient to maintain the necessary greenhouse warming, especially given that the sun was less luminous in the past. The sinks for CO₂ are carbonates stored on continental crust,

carbonatization of oceanic crust, and subduction of these materials. The cycling of carbon into the mantle and back out was faster early in Earth's history. The amount of CO₂ at the surface is tied to its cycling in and out of the oceanic crust and mantle. This system would not have permitted than 10 bars of CO₂ in the atmosphere at any time in the past. In the Hadean, heavy bombardments would have removed CO₂ by weathering of impact ejecta. Episodic pulses of ejecta would drag down CO₂ levels, and the climate would have become very cold in the immediate aftermath. Climate was quite variable then, including around the time that life arose.

Methane is another key atmospheric greenhouse constituent, the one most likely to replace CO₂ during periods of CO₂ drawdown. Methane is relatively stable, compared to other reduced gases such as ammonia. Considering its thermal and biogenic sources, the amount of methane that can be sustained against photochemical destruction and also loss of hydrogen to space would have been about one percent on the young Earth. About a one ocean-equivalent of hydrogen could have been lost in about one billion years with such a methane atmosphere. Thus such an atmosphere could not have been sustained for very long.

Finally, the distribution of impacts during the late heavy bombardment is not well known. By far, most of the impacting mass resides in the largest bodies, therefore chance plays a major role in determining a planet's early history. It would be hard to predict or replicate such a history, even the Moon-forming event. Really large impactors might have arrived as late as 3.8Ga. So many of the differences between planets might be traced to this turbulent, stochastic early period in their histories.

(Kasting – to be added)

(Traub – to be added)

Imke dePater talk. Although much of the focus in Pale Blue Dot work is on the mid-infrared wavelength regime, there may be some very important observations that are or will be possible to make in the radio regime. Angular resolution is important, and single dish radio telescopes are limited to a resolution given by λ/D , where λ is the wavelength and D is the diameter of the radio dish. However, ground-based (and, recently, space-based) radio interferometry is quite well developed, and here the resolution is given by λ/d , where d is the separation between two radio dishes. Given the variety of pairs of separations achieved in an array of telescopes, quite

good images can be constructed at very high angular resolution. Planned arrays for the future include: the Large Millimeter Array, about 50--12 m dishes on a high plateau in Chile, and expected to reach a sensitivity of about 10 nanoJanskys (where a Jansky = $\text{Jy} = 10^{-26} \text{ erg/cm}^2/\text{sec}/\text{ster}/\text{Hz}$ is a unit of flux); and the One Hectare Array, which will operate in the cm range and will be a prototype for the Kilometer Squared array. The latter is expected to reach to sensitivities on the order of 0.1 nanoJy, which will be of more interest to the search for life in other solar systems.

One could hope to detect: thermal emission, as from a modified black body, and including the possibility of maser emission lines; non-thermal emission, of which coherent cyclotron emission is discussed here; and emission from technologically advanced alien societies, which is expected to be contained in a very narrow range of transmission frequencies. Although this latter emission is not discussed further in this talk, Project Phoenix has been set up to systematically and continuously search a large number of stars, in 2.9 million channels of 1 Hz resolution. There the sensitivity is good enough to daily detect the 6 W transmitter on Pioneer 10 at its current distance of 10^{10} km, so that high power transmissions from a distant, technologically advanced society should be detectable.

Coherent cyclotron emission is produced in our solar system by the interaction of planetary magnetospheres with the solar wind and/or satellites of the planet. Representative calculations for currently known extra solar planets show that this emission should be detectable by the Km-squared array. Finding evidence for a magnetic field in a candidate life bearing planet would be a positive sign, since that would mean that the potential biota were protected from high energy particles from space.

At present, thermal emission from terrestrial sized planets would be difficult to detect, though progress in detector technology might make this possible. However, since maser lines can be much brighter in their bandpass than the thermodynamic temperature would allow, they might be detectable with planned systems.

What can be learned from radio studies? The atmospheric opacity, including clouds, will be lower in the radio than in the infrared or optical, so it is potentially possible to probe to greater depths, perhaps all the way to the planetary surface, but certainly to the base of the cloud layers. Zodiacal dust would not be a factor because the emissivity of the dust grains falls rapidly

towards longer wavelengths. In a Gas Giant like Jupiter, radio allows us to potentially probe to depths of a few bars.

Very high resolution spectral observations using heterodyne techniques may make it possible in the future to search at the part per million or billion level. Already many complex organic molecules have been detected in the interstellar medium (ISM); on the order of 120 molecules have been found in the gas phase in the ISM, including amino acids and Glycine. Similarly, a number of organic molecules have been found in various locations throughout the Solar System, i.e. Titan, Neptune, Mars, Io, etc.. These molecules are difficult, if not impossible, to detect and identify in the IR. Therefore, although sensitivity is clearly an issue that needs to be addressed more quantitatively, the radio part of the em spectrum must be kept in consideration for Pale Blue Dot observations in the future.